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Development of a selective low cost absorbing surface based on soot for solar thermal applications

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Abstract

Selective absorber surfaces, based on soot, for solar applications were analyzed to achieve the best optical and thermal properties for a Jorhejpatarnskua solar cooker, which uses a CPC (compound parabolic concentrator) of revolution. The soot was obtained as residue of the biomass combustion in a home, from pine-wood resin sticks and resin combustion. These kinds of soot were analyzed using techniques such as X-ray energy dispersive, differential scanning calorimetry and thermogravimetric analysis. The best optical and thermal properties were presented in resin soot, which coincide with its good characteristics showing the highest C contained and the least number of mineral elements influencing in the thermal decomposition stage. A temperature that went from 200°C to 650°C was reached to begin the thermal decomposition in all kinds of soot. An additional advantage of the resin soot was its yield to produce it.

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Keywords: surface; soot; mineral elements; pine wood-resin sticks; solar cooker; thermogravimetry

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1. Introduction

In order to contribute in improving the environment in the Meseta Purepecha region of Michoacan, Mexico, the intention is to promote the use of Jorhejpatarnskua solar cooker [1-3] in homes. By applying this alternative technology in regard to the traditional chimneys and gas stoves, it also has an advantage in cost savings for families by eliminating the consumption of firewood and gas. However, the operation of these solar cookers should be improved, when the solar absorber is analyzed, which from a thermal point of view should be efficient, requiring to absorb the maximum amount of radiation in the solar spectrum (λ<3mm) and issue the minimum possible to longer wavelengths (λ>a 3mm) [4]. The absorber is a selective surface that comprises particles uniformly distributed in a matrix, which is deposited on a metal substrate [5]. In this case, it is also pointed that a selective surface should be low-cost production, easy application and acquisition, as the case of soot.

Based on the above, a comparative study was performed in three different types of soot, which were; soot by burning resin and wood-resin sticks, and residual soot of firewood in homes. In these three, the first figure of merit was estimated, the stagnation temperature was determined and the absorptance-emittance ratio. Also, the characteristics of the final selective surface may influence the optical and thermal properties. Therefore, it is important a soot characterization through different techniques such as: X-ray energy dispersive analysis, to determine the elemental composition [6]; differential scanning calorimetry, to measure the heat transferred or heat required by a material that will undergo various transformations at different temperatures [7, 8], and a thermogravimetric analysis to measure the mass variation of a sample when is subjected to a temperature program in a controlled atmosphere. The thermogravimetric analysis is generally used along with differential scanning calorimetry to analyze the thermal changes of different materials as a function of temperature [9]. With these analyzes, the soot type and its response characteristics to be the best surface in terms of absorbance and reflectance in the solar collector is reported.

2. Materials and methods

2.1. Soot

Pine wood resin sticks and resin of *Pinus oocarpa* Schiede were collected. Soot samples were obtained out of these materials and also soot located in home was sampled, where soot from firewood and other kinds of biomass were burned when cooking meals. Of each sample, 50g were collected for its respective analysis.

2.2. Optical properties determination in selective surfaces

The performance of a Jorhejpatarnskua solar cooker can be determined by thermal tests as the first merit figure and absortance-emittance ratio.

The first merit figure has been calculated using the equation (1) [10]:

$$F_1 = \frac{T_{estag} - T_{amb}}{I} \qquad (1)$$

where:
T_{estag} is the stagnation temperature in the plate (tray) and T_{amb} and I are the room temperature and the insolation on the horizontal surface at the time stagnation temperature is reached, respectively.

Absorptance-emittance ratio using the following equation (2) was calculated [4], taking into account that the heat exchange might not be considered by conduction and convection in the solar cookers' absorber.

$$\frac{\alpha}{\varepsilon_{ir}} = \frac{\sigma T_{estag}^4}{I} \qquad (2)$$

where:

$\sigma = 5.67 x 10^{-8} \frac{W}{m^2 K^4}$ is the Stefan-Boltzmann constant

α absorptance in the visible,

ε_{ir} is the infrared emittance.

The experimental design consists of an array of three 400 Watts incandescent lamps and two of 1000 Watts, placed at 30 cm above the pot, providing irradiance controlled conditions without the presence of wind flows. The absorber surface temperature was measured with a K-type surface sensor. For the irradiance data, a solarimeter "daystar meter" was used, and a digital stopwatch to record the time. This design for thermal analysis was also used by González et al. [11], too.

2.3. Analysis using X-ray energy dispersion

X-ray energy dispersion analysis is a technique used for identifying the elemental composition of a sample or small area of interest in the same. During X-ray energy dispersion analysis, a sample is exposed to an electron beam in a Scanning Electron Microscope (SEM). These electrons collide with electrons in the sample, causing some of them to be removed from their orbits. Free spaces are refilled by higher energy electrons emitting X-rays in the process. By analyzing the emitted X-rays, the elemental composition of the sample can be determined. X-ray energy dispersion analysis is a powerful tool for microanalysis of elementary constituents in a semi-quantitative way [6]. The microanalysis of the samples was obtained by a JEOL JSM-6300 Scanning Electron Microscope (SEM) equipped with an Energy Dispersion Spectrometer (EDS) attached for chemical composition measurements; the acceleration voltage was 15 kV. Many researchers have applied this technique to biomass in different ways. For example Szemmelveisz et al. [12] analyzed the ash composition trying to determinate which of the compounds are more important to slagging processes.

2.4. Analysis using differential scanning calorimetry

For differential scanning calorimetry studies, Ramp method in a DSC Q2000 V24.10 Build 122 was applied. For this analysis 3.4 mg of soot obtained in a home, 0.8 mg of pine wood-resin sticks soot and a sample (1.8 mg) of resin soot were employed, all in a temperature range of 0 to 600 °C. Technique used by Fernandez [6], as well.

2.5. Thermogravimetric analysis

Non-isothermal thermogravimetric analysis were carried out in a gravimetric thermobalance system, using a TGA Q5000 equipment (standard model), in a ramp of 25-800 °C. The thermobalance automatically measures the sample weight and the temperature as a time function. Experiments were carried out in inert atmosphere (N_2), and in an air atmosphere, for a total flow rate of 25 ml/min, employing a sample mass of 17.718 mg from home soot, approximately 0.418 mg from pine wood-resin sticks soot sample and for resin soot 1.618 mg were utilized. The sample temperature was increased from room temperature up to 800 °C at a heating rate of 10 °C/min. This thermo analytical technique provides information in a straightforward manner [13-17].

3. Results and discussion

3.1. Determination of optical and thermal properties in selective surfaces

From the point of view of the optical and thermal properties, obtained by applying a standardized test for the performance study of solar cooker, the best results were obtained when using resin soot, in stagnation temperature, as well as for the first merit figure and absorptance-emittance ratio (Table 1). There was no significant difference between the surfaces produced with selective pine wood-resin sticks soot regarding home soot. Testing without selective surface was made to see that the optical and thermal properties obtained improve significantly with the use of a selective surface based in soot.

Table 1. Optical and thermal properties of the selected surfaces.

Material	**Stagnation temperature (°C)**	**Ambient temperature (°C)**	**First merit figure**	**Absorptance-emittance ratio**
Soot from home	138	19.5	0.156	2.13
Pine wood-resin sticks soot	141	21	0.158	2.19
Resin soot	148	20	0.168	2.34
Without selective surface	110	23	0.114	1.61

3.2. Analysis using X-ray energy dispersion

Metallic elements appear as products present of environmental pollution in which soot is found and by its production method (Fig. 1). In general, the results are similar to those reported by Fengel and Wegener [18] for several wood species.

Here the Cu, Fe and Zn presented in pine wood-resin sticks soot are obtained from soil and environment.

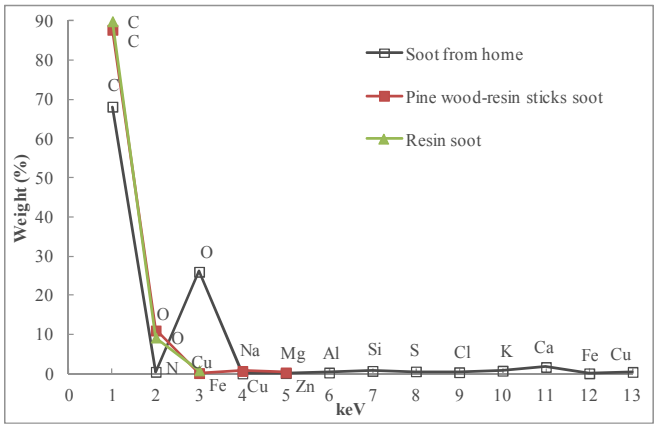

Fig. 1. Elemental composition determined by Energy Dispersion Spectrometer for three soot samples

The resin soot has the highest purity, and hence it has a higher percentage of C.

3.3. Analysis trough differential scanning calorimetry

3.3.1. Soot from home

A sharp peak at a temperature of 155 °C in the Fig. 2 is observed, which is related to a thermal decomposition stage of soot, which may be catalyzed by the minerals already seen in the X-ray energy dispersion analysis. As regards the chemical composition, sharp peak refers homogeneity of the transformed material which process could be catalyzed by the present minerals, decreasing a possible heterogeneity in the chemical composition of soot. After at 215 °C another peak is observed, less acute, that represents the chemical heterogeneity of the material processed. This heterogeneity may be due to the organic substances and the broad range of minerals present in the soot composition.

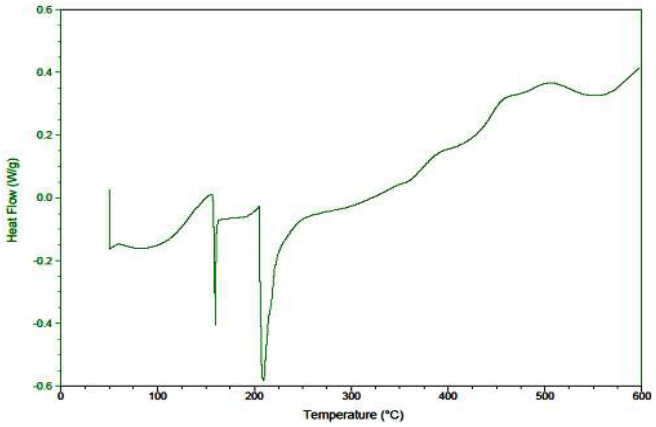

Fig. 2. Differential scanning calorimetry analysis of soot from home

3.3.2. Pine wood-resin sticks soot

Two sharp peaks at 50 °C and another at 376 °C are shown in Fig. 3, the second peak is slightly less sharp than the first, both peaks show greater homogeneity in the chemical composition of soot studied. This soot has fewer minerals content than soot from home, in this case the presence of minerals contributed to the heterogeneity of the material studied.

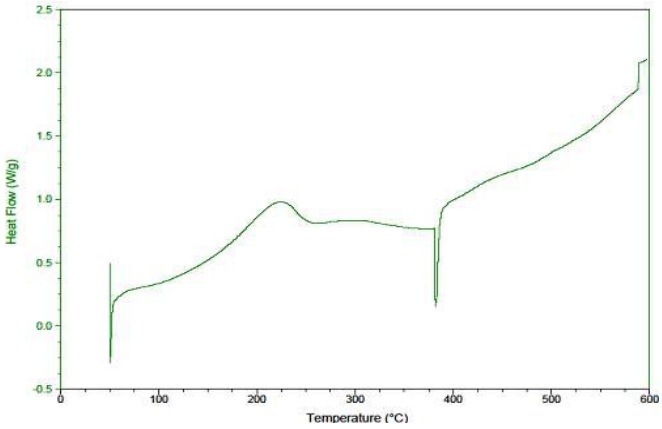

Fig. 3. Differential scanning calorimetry analysis of pine wood-resin sticks soot

3.3.3. Resin soot

A single peak at 437.5 °C is observed in Fig. 4. If this soot is consider to have the fewer mineral (only one), then, the hypothesis about mineral influence on the decomposition of soot is confirmed, since the observed peak is very sharp it gives homogeneity information on the chemical composition of decomposed material.

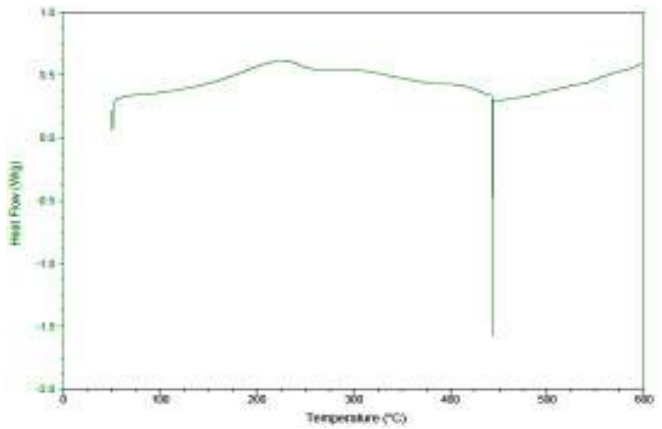

Fig. 4. Differential scanning calorimetry analysis in resin soot

Also, generally, there is an involvement of the minerals as catalysts in the process of thermal soot decomposition, facilitating thermal conversion processes that occur at lower temperature, thus decreasing the presence of mineral; it increases the temperature at which occurs decomposition. Three samples for thermal conversion processes are almost predominantly exothermic (ΔH>0).

3.4. Thermogravimetric analysis

According to thermogravimetric analysis the pyrolytic decomposition of soot was performed in the interval between 200 and 650 °C (Fig. 5). The thermogravimetric decomposition for lignocellulosic materials occurs in the range of 200 to 500 °C [19], this is showed by Cordero, et al. [20], Raveendran and Ganesh, [21] and Yang, et al. [22]. Mainly for soot from home and pine wood-resin sticks soot, there is a greater range of decomposition extended to 600-650 °C, and greater heterogeneity in the integral curves, this is given by the presence of different metallic elements in samples which absorb energy at different temperatures displaying no decomposition area of maximum pending as with resin soot having no metallic elements, shows a breakdown defined mainly in the range 490 ºC and 650 ºC (Fig. 5). For a same value of temperature a greater transformation is observed in soot from home and pine wood-resin sticks soot because of the catalyzing process by minerals. The thermal decomposition of soot to ashes is given at 800 °C.

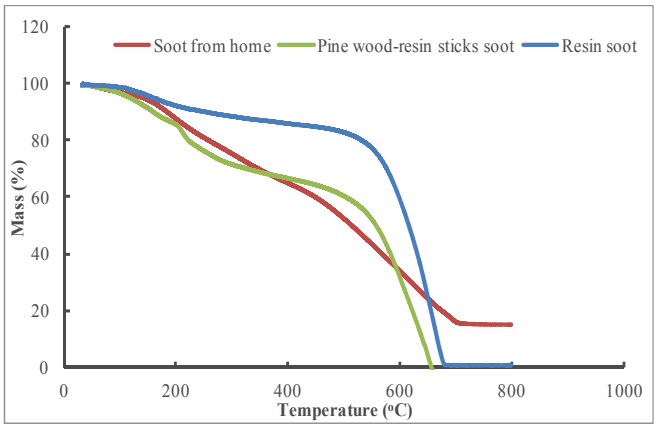

Fig. 5. Thermogravimetric analysis in inert atmosphere for soot samples

4. Conclusion

Using a soot surface is better than not applying it on the pot. In regards to the three kinds of soot that were analyzed, resin soot showed the best optical and thermal properties for Jorhejpatarnskua solar cooker. This is because the biggest percentage with the C element was presented in resin soot, in reference to other elements. This kind of soot had three elements, only, including Cu as mineral, so resin soot had least influence in the thermal decomposition stage. All soot started its thermal decomposition from 200 to 650°C. In addition to the good characteristics presented in resin soot, the best yield for its production was obtained.

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